Final state interactions and photon-induced charm production

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Core message

- Near-threshold $D^{(*)}_{(s)}\bar{D}^{(*)}_{(s)}$ production is strongly shaped by coupled-channel final-state interactions.
- FSI produces a characteristic charged/neutral pattern and changes line shapes and expected meson yields;
- Photon-induced processes provide clean environments to probe molecular charm dynamics
- FSI can describe the dynamical generation of meson molecules

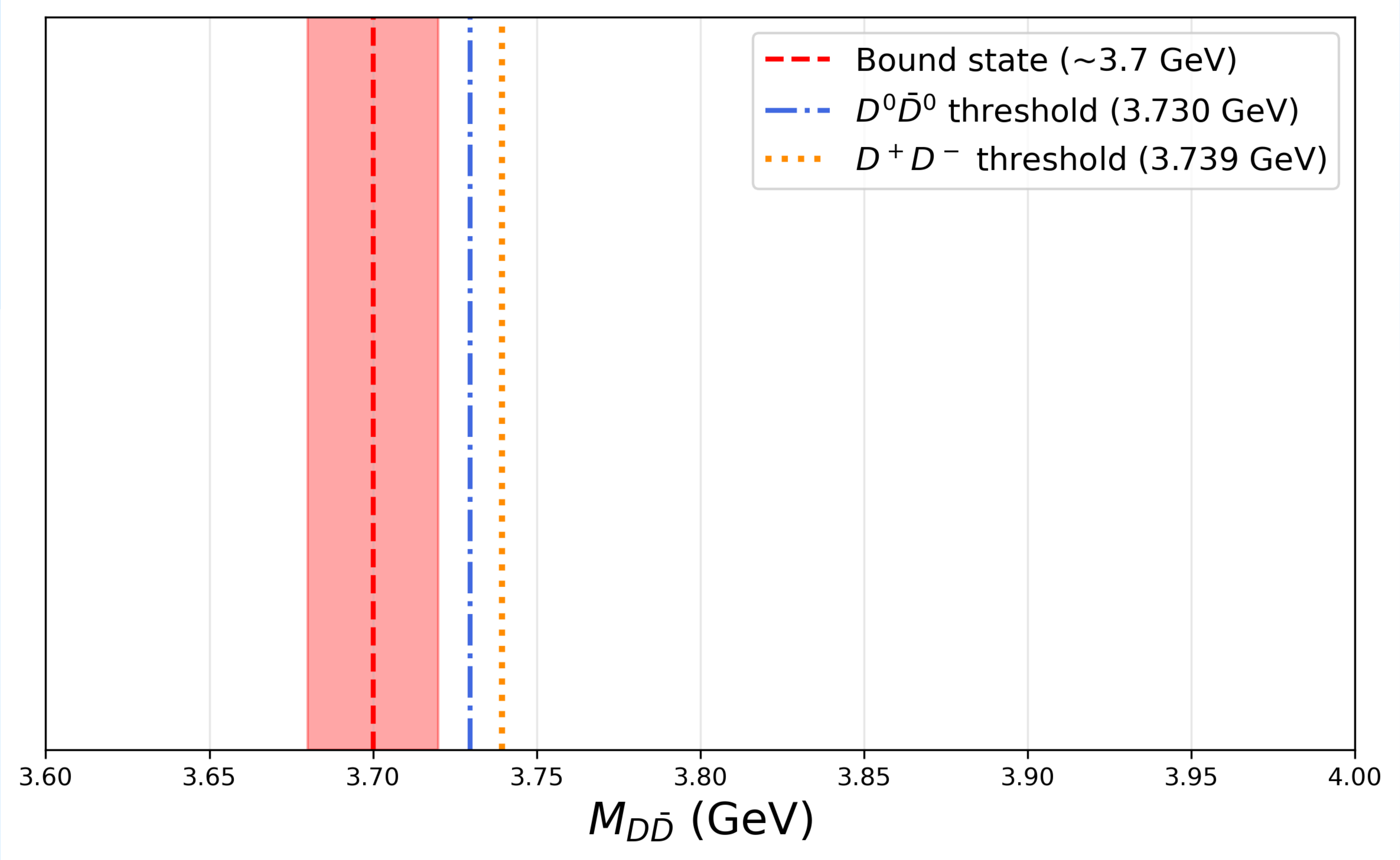
$$\gamma\gamma \to D^{(*)}_{(s)}\bar{D}^{(*)}_{(s)} \quad + \quad D^{(*)}_{(s)}\bar{D}^{(*)}_{(s)}\ \text{FSI} \longrightarrow d\sigma/dW, d\sigma/dY, N_{events}, \ldots$$

Near-threshold charm dynamics

Gamermann, et al. Phys.Rev.D 76 (2007) 074016

Prelovsek, et al. JHEP 06 (2021) 035

Nieves, Pavon Valderrama. Phys.Rev.D 86 (2012) 056004



- Many charmonium-like states lie close to open-charm thresholds.
- A scalar $D\bar{D}$ molecule candidate, often associated with $X(3700)$, appears in coupled-channel approaches.
- Production observables can reveal how this dynamics affects line shapes and yields.

Why $\gamma\gamma$ production?

$$A \to A + \gamma, \qquad e/A \to e/A + \gamma$$

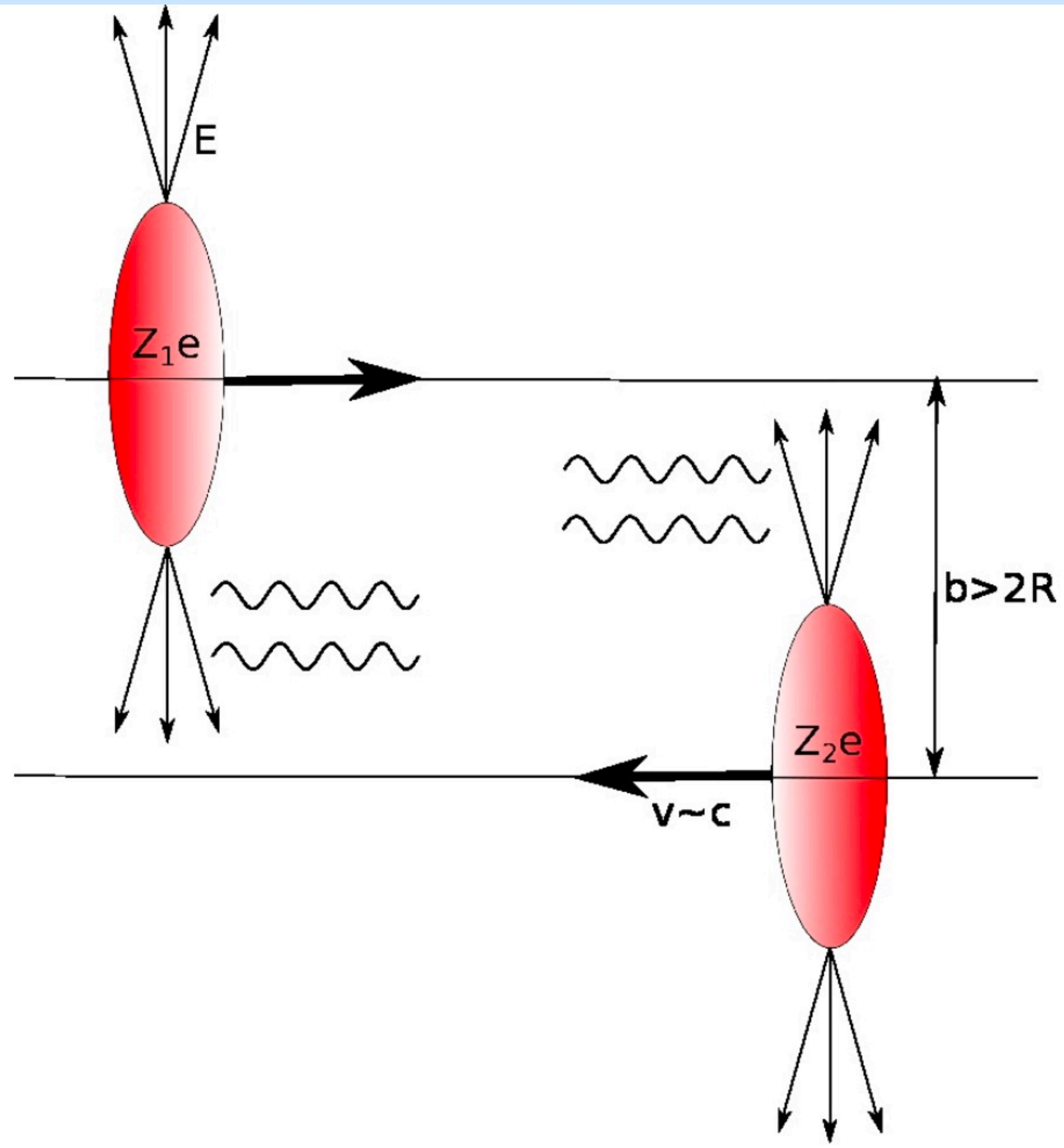
$$\gamma\gamma \to D\bar{D}$$

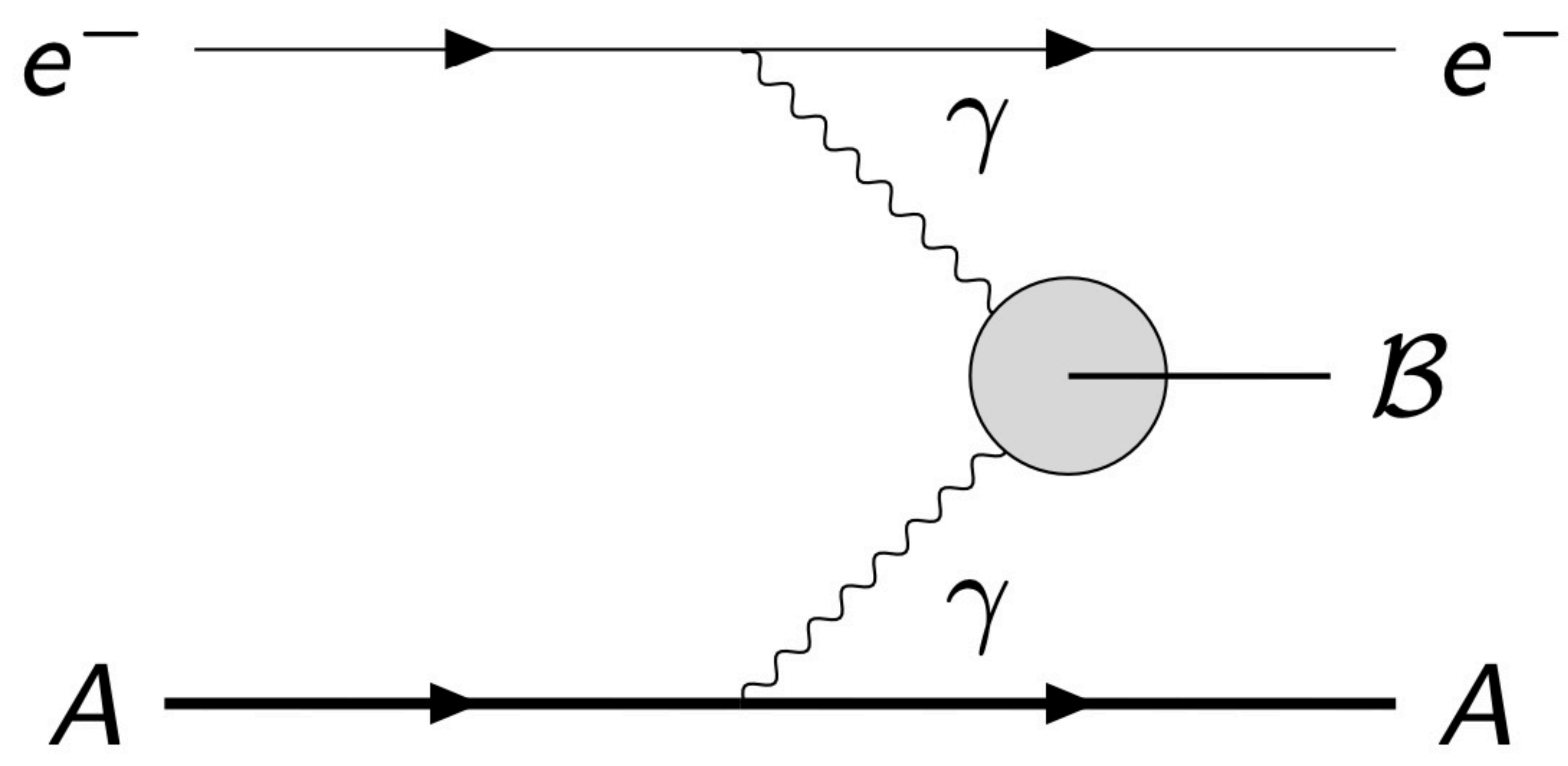
- Electromagnetic initial state
- Relatively clean background
- Same subprocess can be studied in UPC and EIC environments

UPC: No hadronic overlap, rapidity gaps

EIC: No Pomeron or hadronic contribution from the electron side

Bertulani, Klein, Nystrand. Ann.Rev.Nucl.Part.Sci. 55 (2005) 271-310

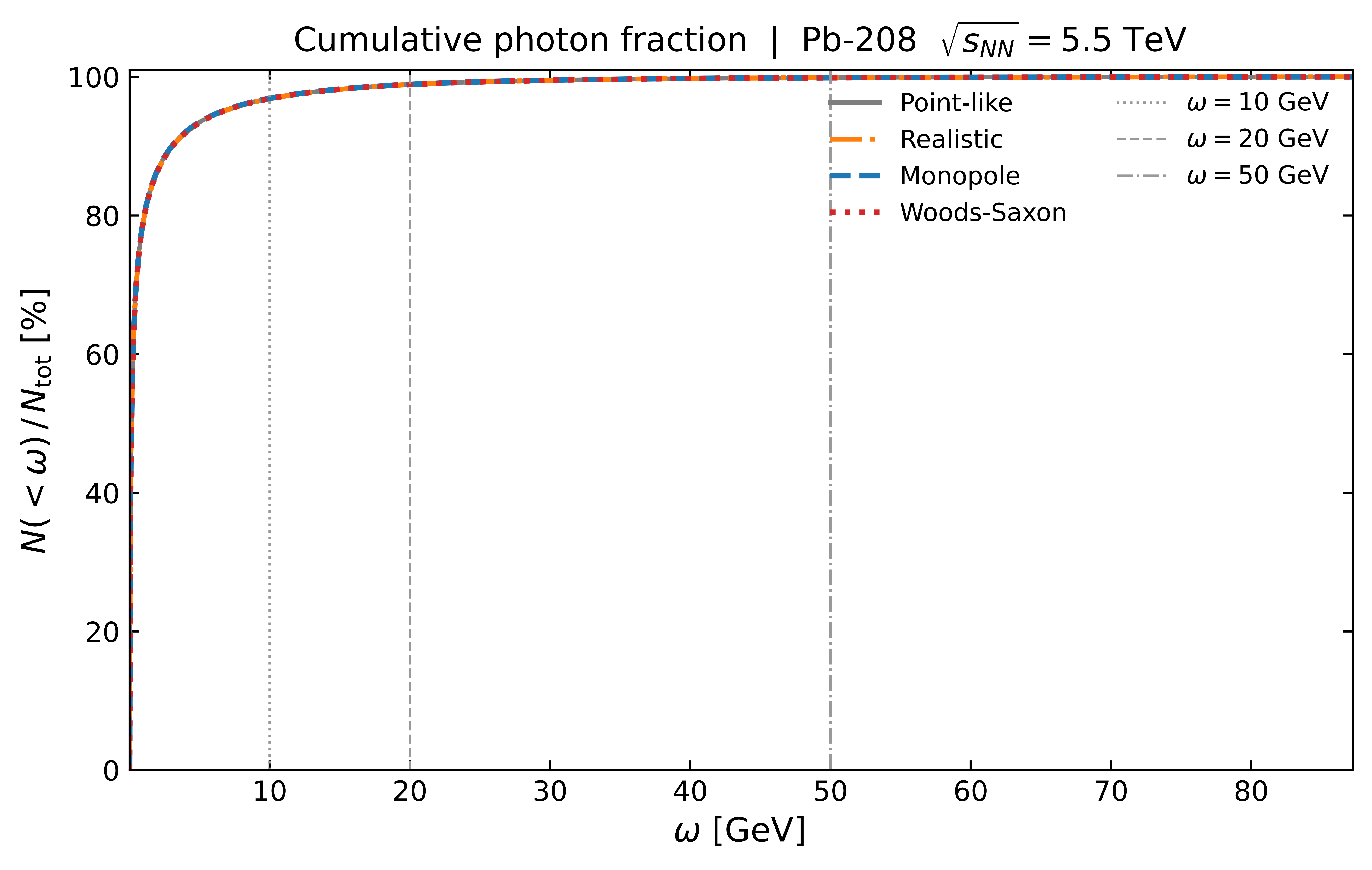




Why $\gamma\gamma$ production?

Useful for near threshold physics!

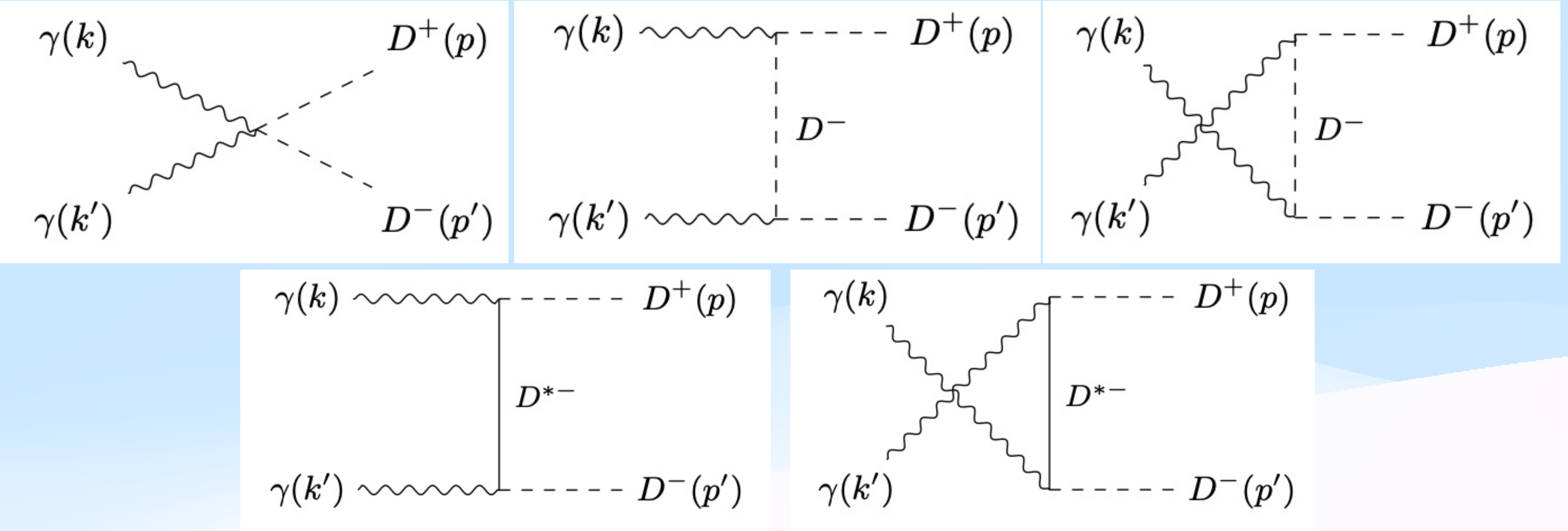
$n(\omega)$ **is larger at lower** ω



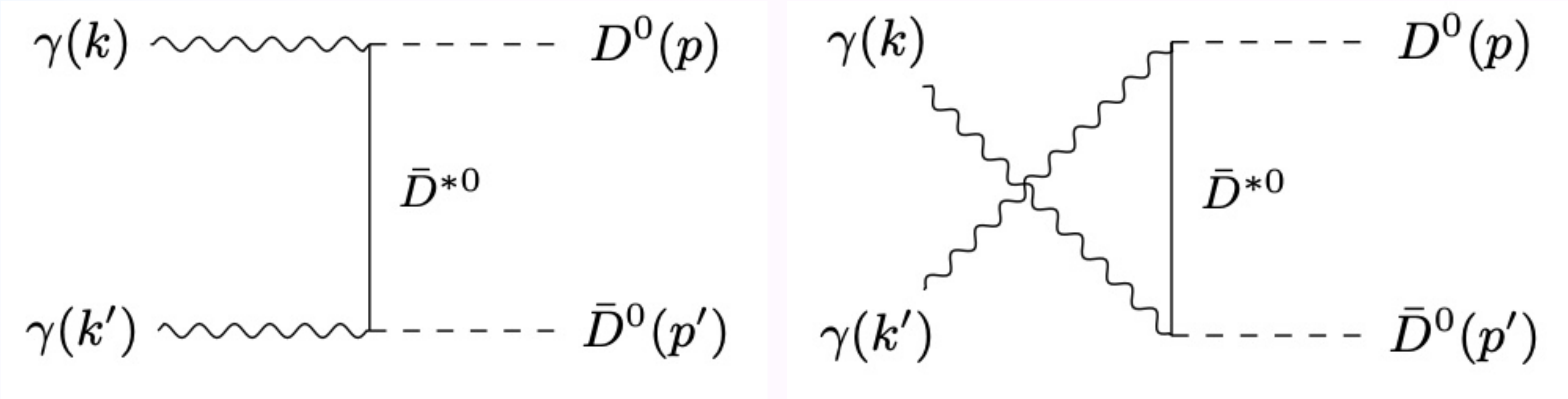
Bertulani, Klein, Nystrand. Ann.Rev.Nucl.Part.Sci. 55 (2005) 271-310

Bare $\gamma\gamma \to D\bar{D}$ production

Charged channel: $\gamma\gamma \to D^+D^-$
Scalar QED + $D^{*\pm}$ exchange



Neutral channel: $\gamma\gamma \to D^0\bar{D}^0$
Only D^{*0} exchange



The two charge channels already have different bare production mechanisms before FSI

Since photons distinguish charge states, production is computed in the charge basis instead of isospin.

Near-threshold S-wave projection

$|\vec{q}| \to 0$ near threshold

$l > 0$ suppressed by powers of $|\vec{q}|^l$

S-wave $\to J^{PC} = 0^{++}$

Near threshold, we focus on the scalar 0^{++} component.

$$M_0 = \frac{1}{2} \int_{-1}^{1} d(\cos\theta) M(s, \cos\theta)$$

$$\hat{\sigma}(\gamma\gamma \to D\bar{D}) = \frac{\beta_D}{32\pi s} |M_0(s)|^2$$

Coupled-channel FSI

Oller, Oset, Pelaez. Phys.Rev.D 59 (1999) 074001

$$D^+D^- \leftrightarrow D^0\bar{D}^0$$

$$T(s) = V(s) + V(s)G(s)T(s)$$

$$T(s) = [1 - V(s)G(s)]^{-1}V(s)$$

The produced pair can rescatter before being observed.

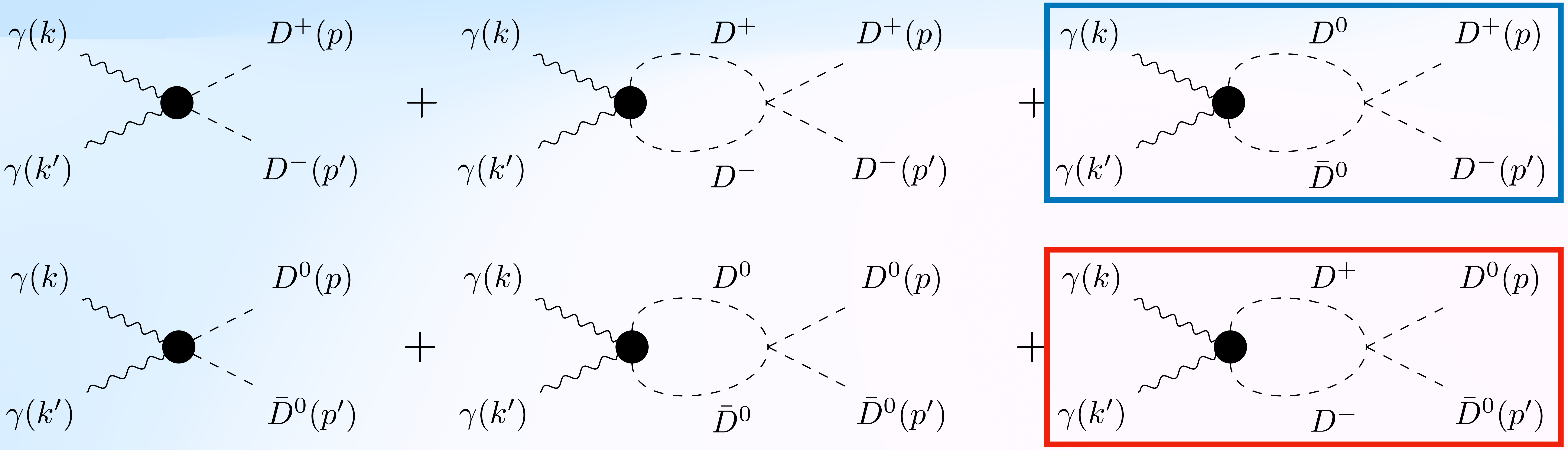
V: Interaction kernel G: Two meson loop T: Rescattering amplitude.

Dressed production amplitude

$$M_i^{dressed} = M_i^{bare} + \sum_{j=1}^{2} M_j^{bare} G_j T_{ji}\,.$$

$$M_{ch}^{dressed} = M_{ch}^{bare} + M_{ch}^{bare} G_{ch} T_{11} + M_n^{bare} G_n T_{12}$$

$$M_n^{dressed} = M_n^{bare} + M_{ch}^{bare} G_{ch} T_{21} + M_n^{bare} G_n T_{22}$$



Our result: Neutral feeds charged; Charged suppresses neutral

From $\gamma\gamma$ subprocess to UPC/EIC observables

$PbPb$ UPC: $\gamma_{Pb}\gamma_{Pb} \to D\bar{D}$

eAu EIC: $\gamma_e\gamma_{Au} \to D\bar{D}$

Equivalent Photon Approximation:

$$\sigma = \int d\omega_1 d\omega_2 n_1(\omega_1) n_2(\omega_2) \hat{\sigma}_{\gamma\gamma\to D\bar{D}}(\omega_1, \omega_2)$$

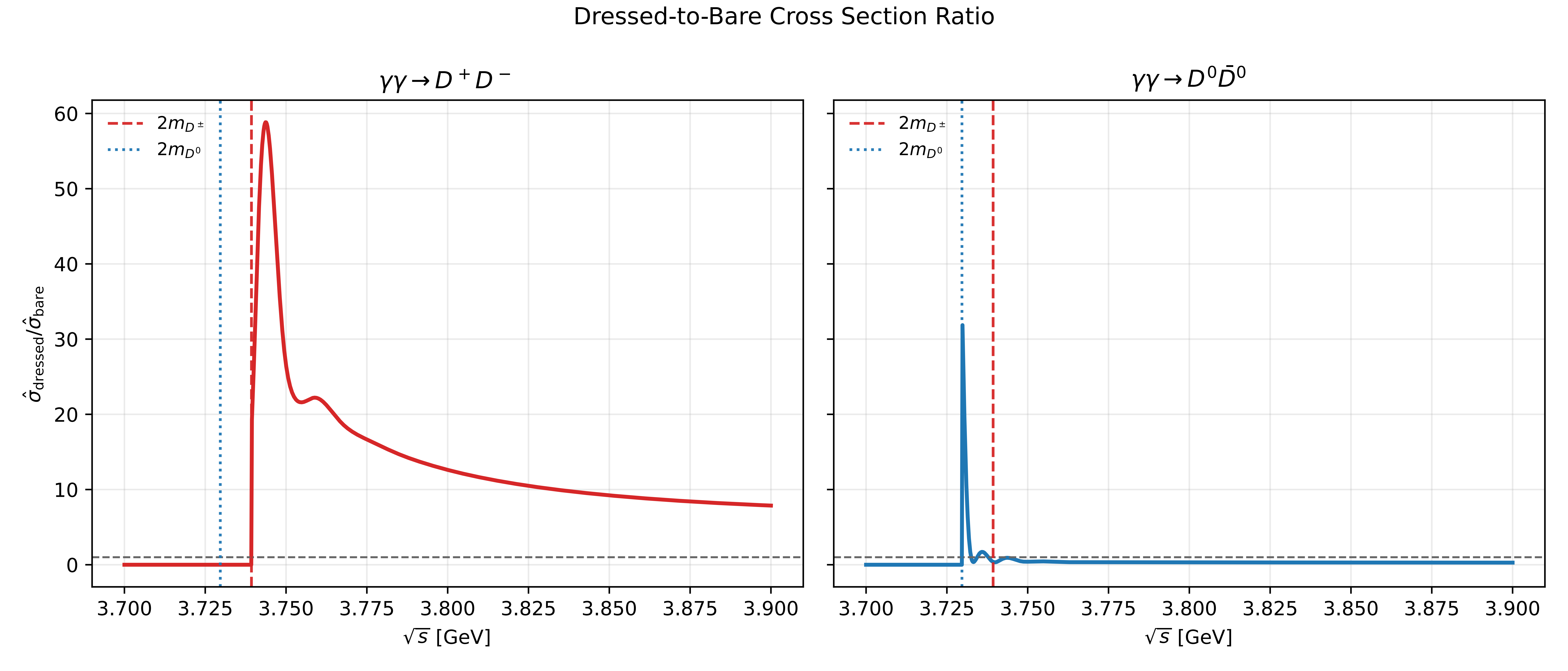
↓ $\omega_{1,2} = \frac{W}{2} e^{\pm Y}$

$$\frac{d^2\sigma}{dWdY} = \frac{2}{W} f_1(\omega_1) f_2(\omega_2) \hat{\sigma}_{\gamma\gamma\to D\bar{D}}(W) \,.$$

UPC and EIC: Different photon fluxes, same $\gamma\gamma \to D\bar{D}$ subprocess

Subprocess result: FSI signature

$$R_{FSI} = \frac{\hat{\sigma}_{dressed}}{\hat{\sigma}_{bare}}$$

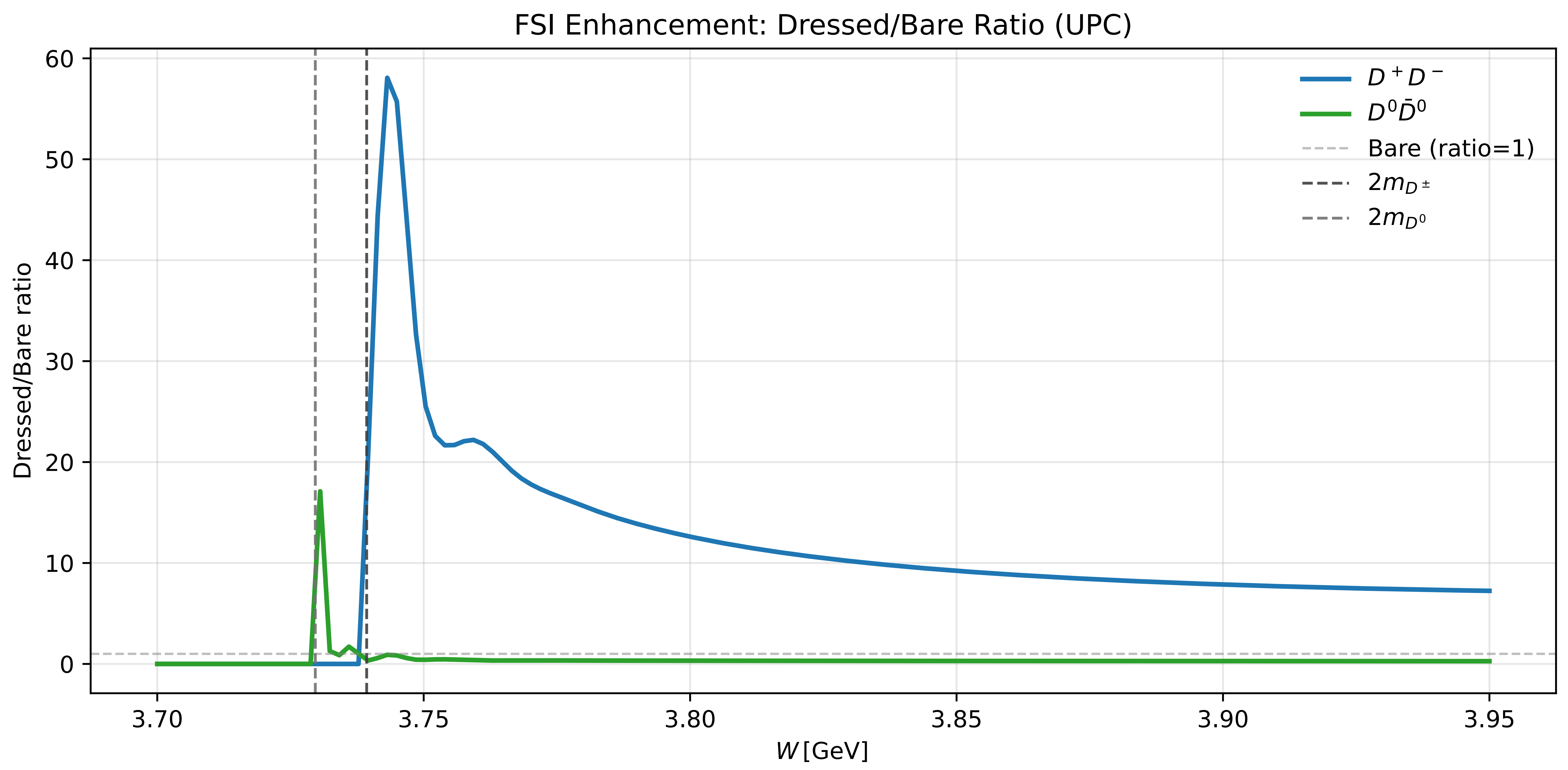


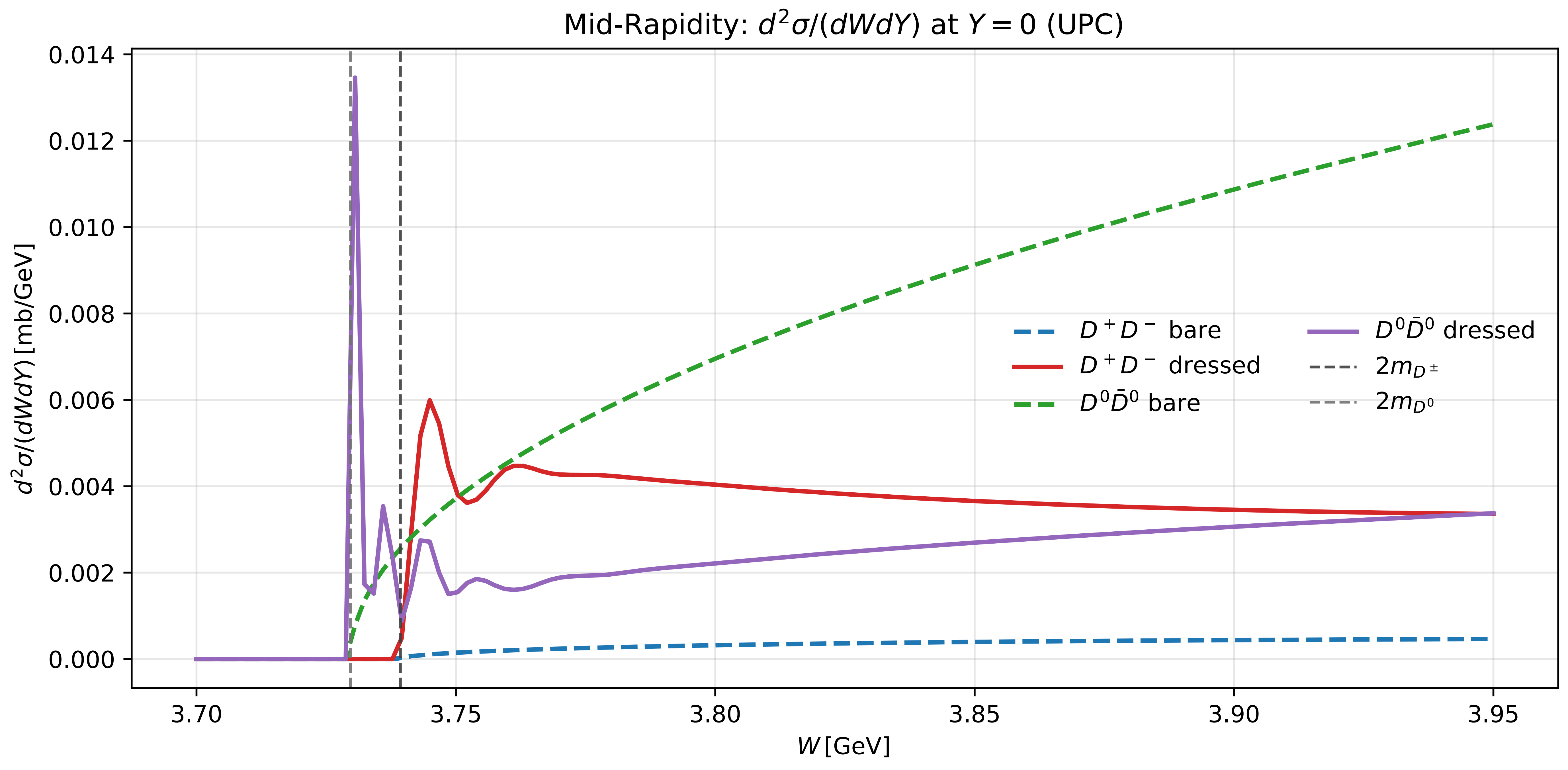
- D^+D^- enhanced by FSI: $R^{ch}_{FSI} \sim 10$
- $D^0\bar{D}^0$ suppressed by FSI: $R^{n}_{FSI} \sim 0.3$
- Strongest structure close to the $D\bar{D}$ thresholds

UPC observables

The FSI pattern survives after convolution with the UPC photon flux

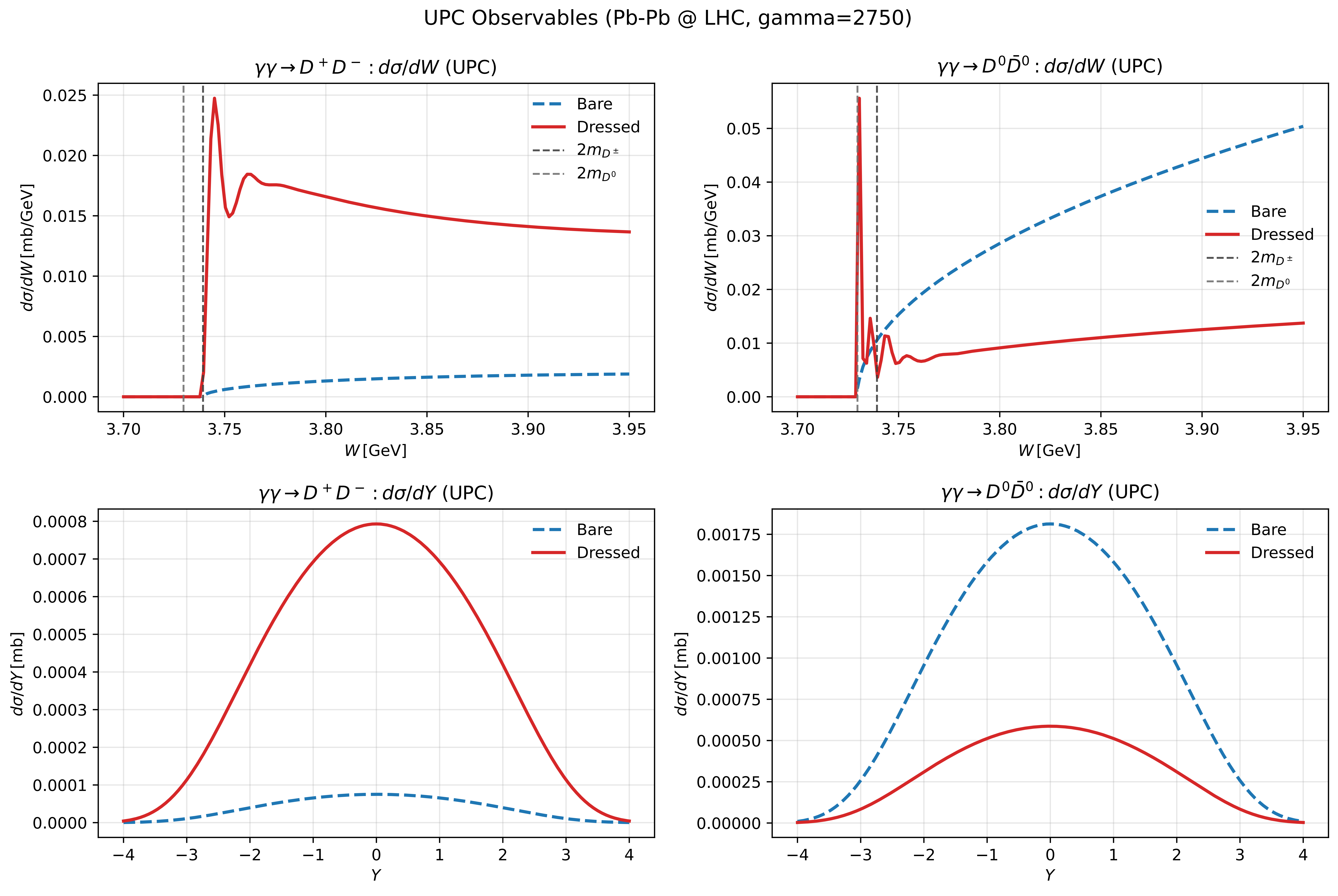
$$R_{FSI}^{UPC} \approx R_{FSI}^{\gamma\gamma}$$





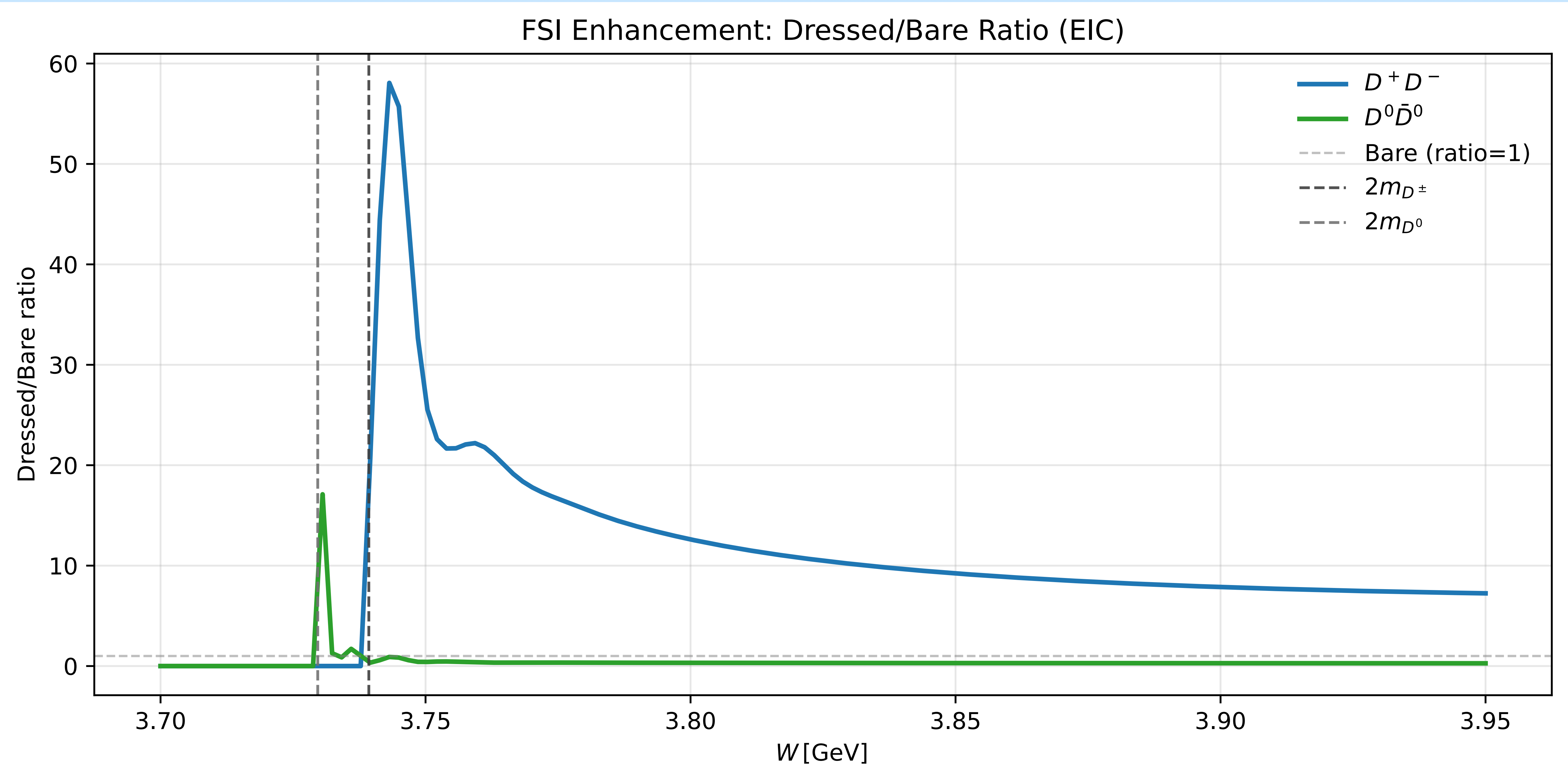
UPC observables

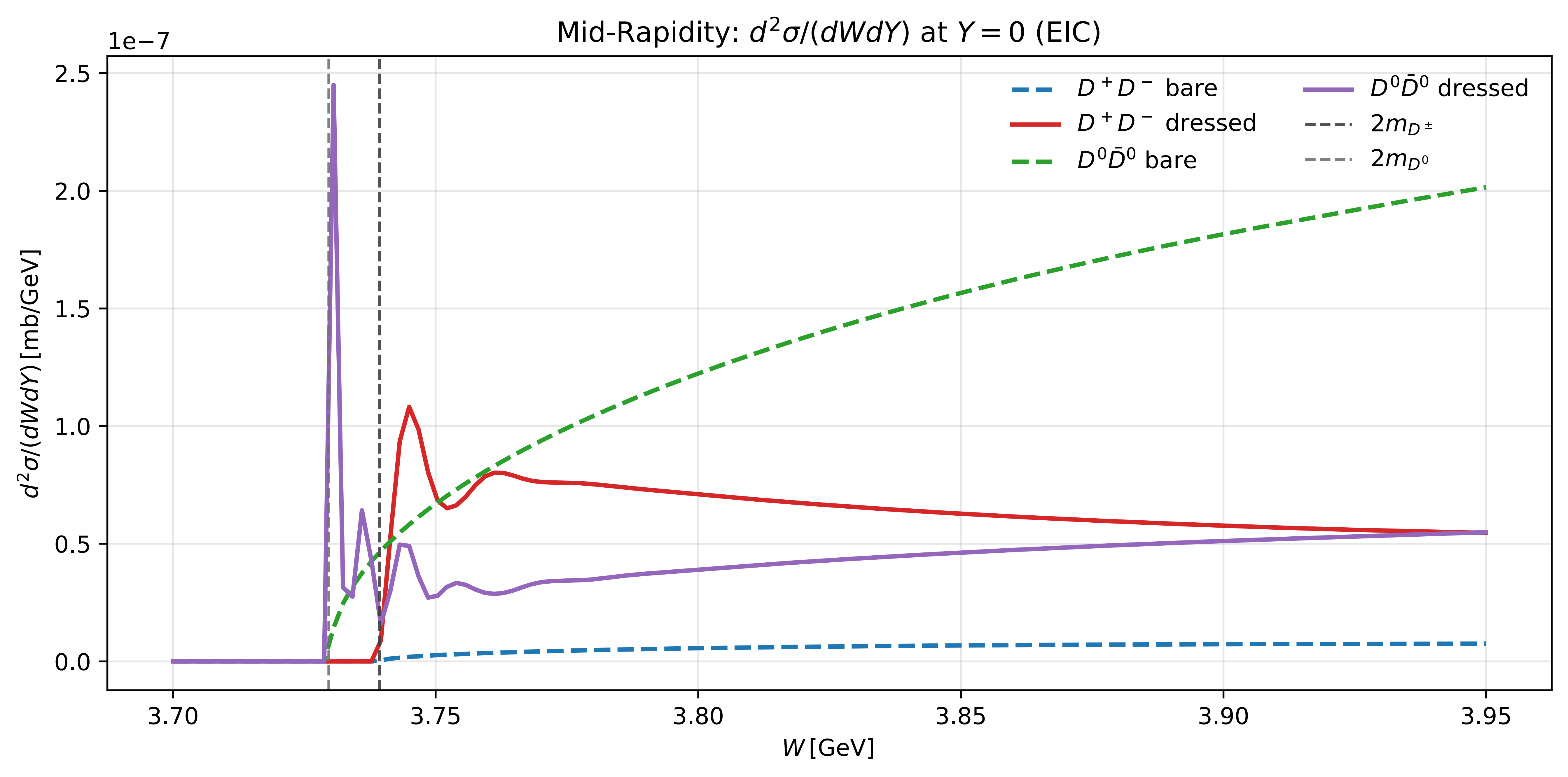
- Symmetric rapidity distribution
- Presence of bound state mostly seen on the $d\sigma/dW$ line shapes



EIC observables

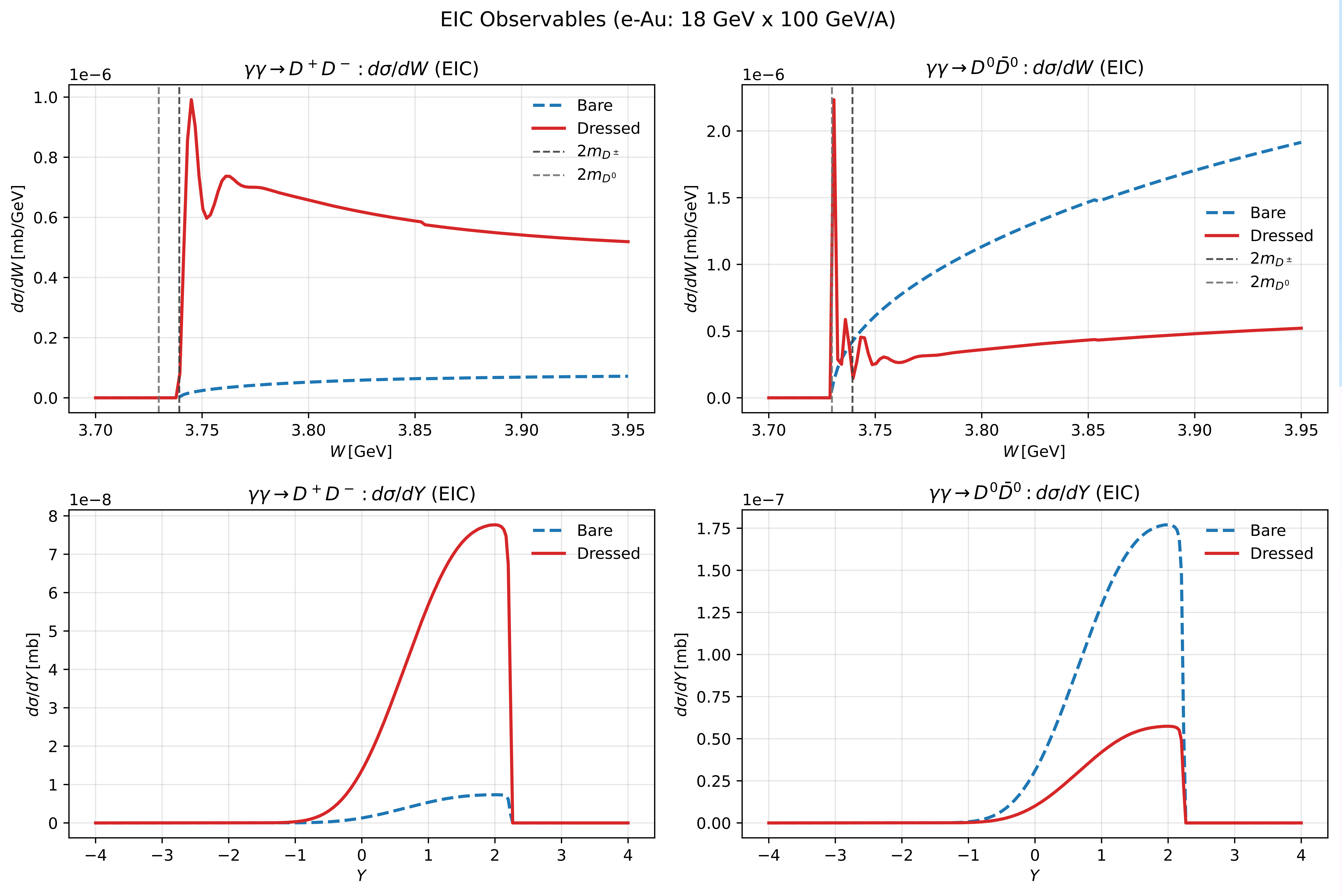
Similar FSI pattern despite different photon fluxes.





EIC observables

- Asymmetric rapidity distribution
- Presence of bound state mostly seen on the $d\sigma/dW$ line shapes

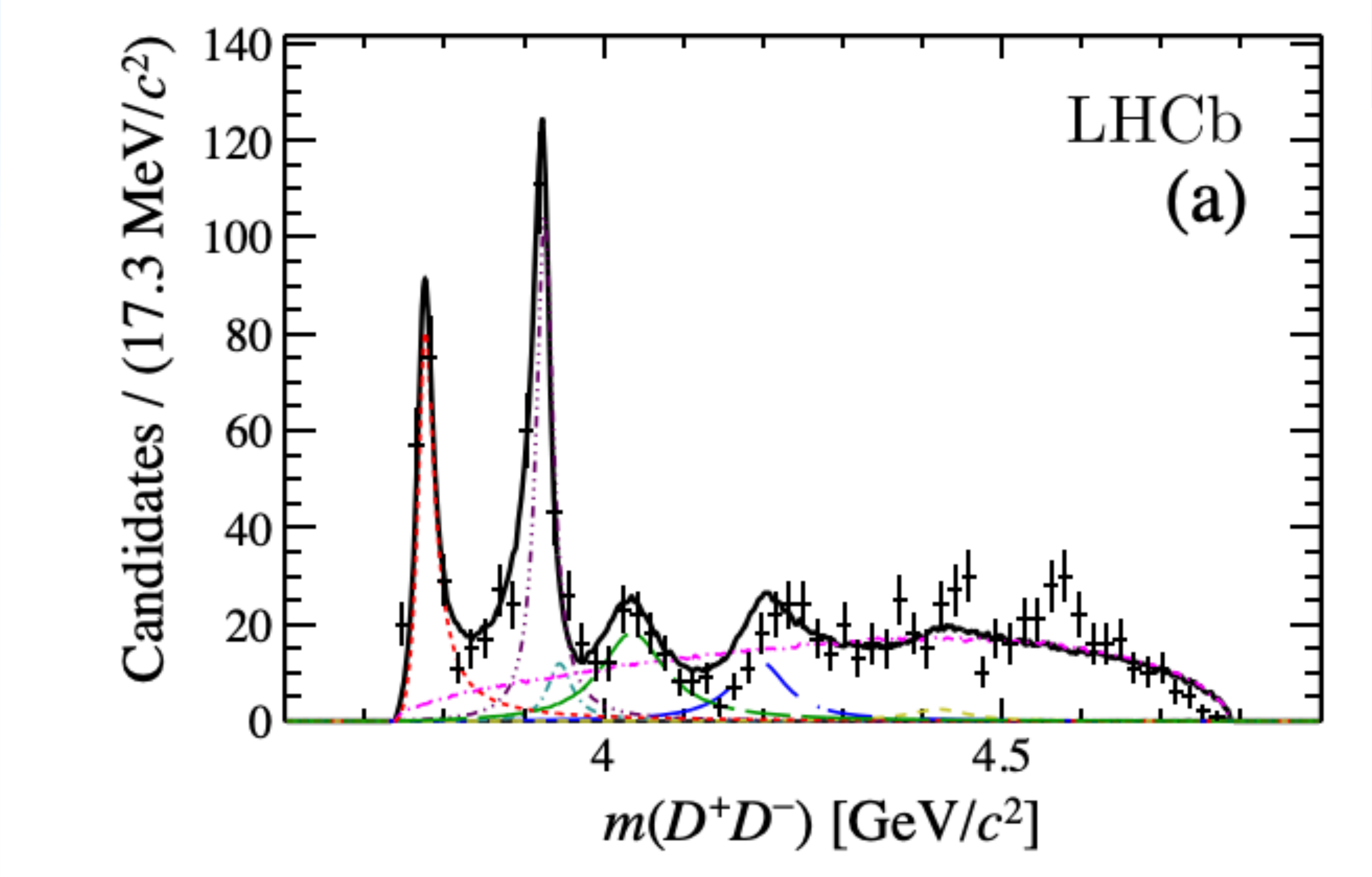


Outlook: larger coupled-channel systems

$$D\bar{D}, \quad D_s\bar{D}_s, \quad D^*\bar{D}^*, \quad D_s^*\bar{D}_s^*$$

PP sector $\leftrightarrow X(3700)$ $\quad$ VV and $D_s^{(*)}\bar{D}_s^{(*)}$ sector $\leftrightarrow X(3960)$

- Extend the coupled channel framework beyond $D\bar{D}$
- Include $D_s^{(*)}\bar{D}_s^{(*)}$ and vector channels
- Can describe both $X(3700)$ and $X(3960)$
- Connect scattering dynamics with production observables



PHYS. REV. D 102, 112003 (2020)

PP Sector

- Describes a candidate $X(3700)$ using only PP coupled-channels

Dynamically generated open and hidden charm meson systems

D. Gamermann,[1] E. Oset,[1] D. Strottman,[1] and M. J. Vicente Vacas[1]
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(Received 18 December 2006; revised manuscript received 25 June 2007; published 16 October 2007)

- Describes both a candidate $X(3700)$ and a 0^{++} structure at around ~ 3930 MeV using only PP coupled-channels, but changing the interaction and applying some approximations

$X(3960)$ seen in $D_s^+ D_s^-$ as the $X(3930)$ state seen in $D^+ D^-$

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We perform a calculation of the interaction of the $D\bar{D}$, $D_s\bar{D}_s$ coupled channels and find two bound states, one coupling to $D\bar{D}$ and another one at higher energies coupling mostly to $D_s^+ D_s^-$. We identify this latter state with the $X_0(3930)$ seen in the D^+D^- mass distribution in the $B^+ \to D^+D^-K^+$ decay, and also show that it produces an enhancement of the $D_s^+ D_s^-$ mass distribution close to threshold which is compatible with the recent LHCb observation in the $B^+ \to D_s^+ D_s^- K^+$ decay which has been identified as a new state, $X_0(3960)$.

VV Sector

PHYSICAL REVIEW D **80,** 114013 (2009)

$Y(3940)$, $Z(3930)$, and the $X(4160)$ as dynamically generated resonances from the vector-vector interaction

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(Received 24 July 2009; revised manuscript received 28 October 2009; published 15 December 2009)

Describes several structures at around ~ 3950 MeV, including 0^{++} only using VV coupled-channels

What if the X(3960) is a VV structure appearing in PP channels?

PP and VV coupled-channels

PHYSICAL REVIEW D **90,** 114023 (2014)

$X(3872)$ production in high energy heavy ion collisions

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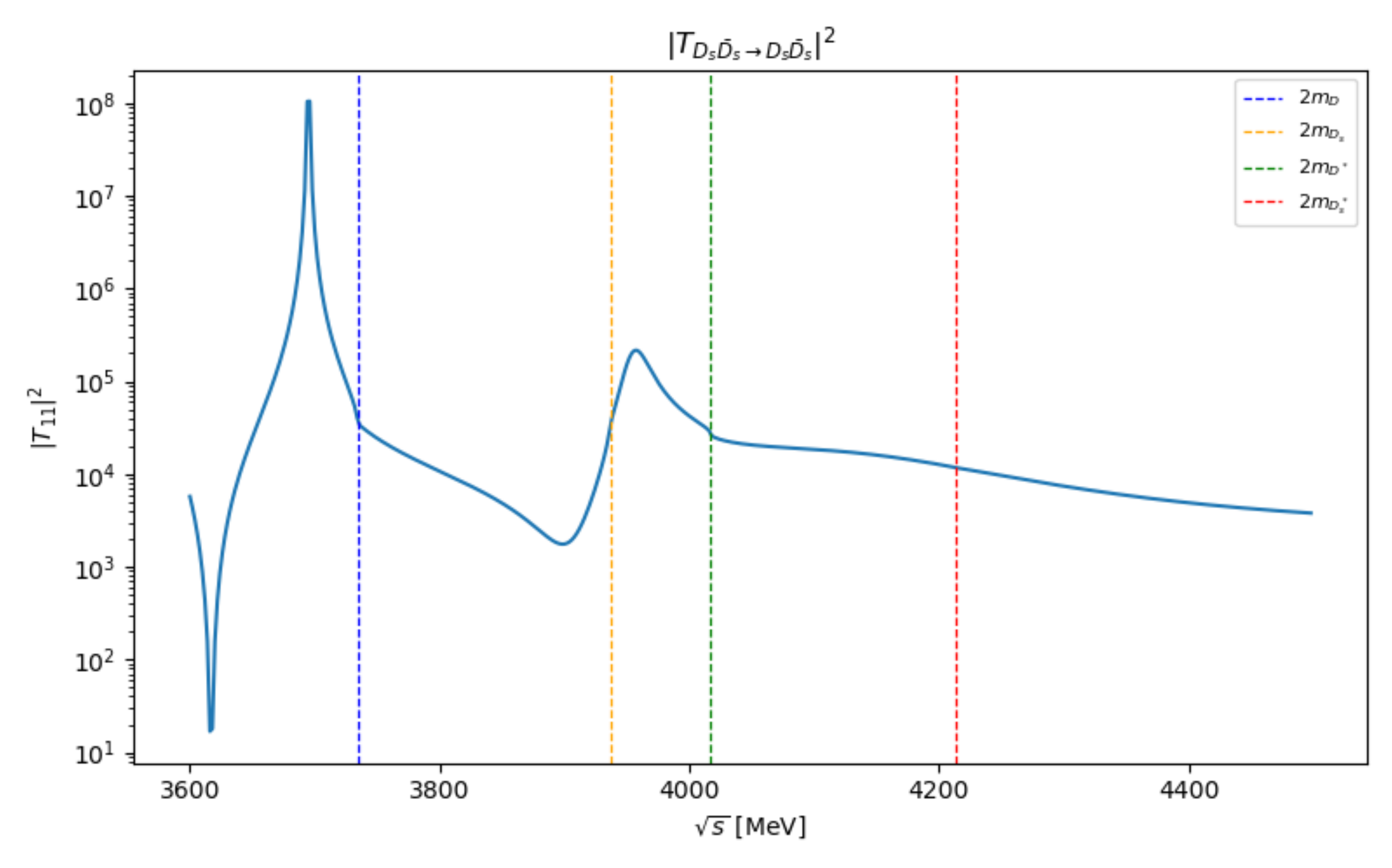
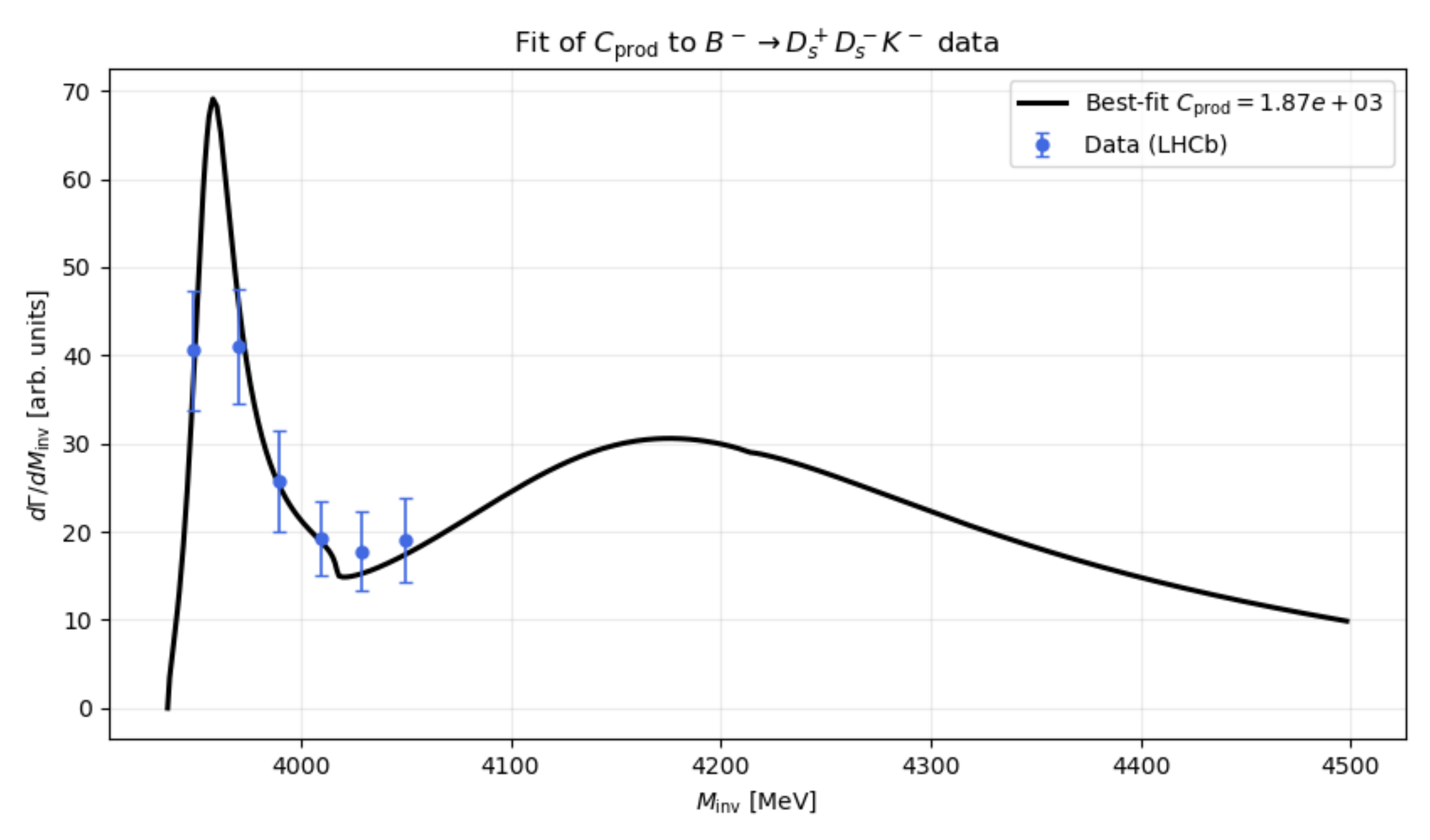
(Received 8 June 2014; published 18 December 2014)

Interaction Lagrangians that couple both P and V mesons

Results





The coupling between sectors is able to describe the data!

Conclusions

- Coupled-channel FSI strongly modifies near-threshold $\gamma\gamma \to D\bar{D}$;
- The effect is channel dependent: D^+D^- enhancement and $D^0\bar{D}^0$ suppression;
- UPC and EIC provide complementary environments, while the FSI ratio is mainly controlled by the subprocess;
- FSI affects both line shapes and expected yields.
- Extending the coupled channels can provide a description of structures at both PP and VV sectors!

Obrigado!

IFUSP
Instituto de Física da USP

FAPESP

Backup

$D^*(2010)^{\pm}$ **DECAY MODES**

$D^*(2010)^-$ modes are charge conjugates of the modes below.

Mode		Fraction (Γ_i / Γ)	Scale Factor/ Conf. Level	P(MeV/c)
Γ_1	$D^0\pi^+$	(67.7 ± 0.5) %		39
Γ_2	$D^+\pi^0$	(30.7 ± 0.5) %		38
Γ_3	$D^+\gamma$	(1.6 ± 0.4) %		136

$D^*(2007)^0$ **DECAY MODES**

$\overline{D}^*(2007)^0$ modes are charge conjugates of modes below.

Mode		Fraction (Γ_i / Γ)	Scale Factor/ Conf. Level	P(MeV/c)
Γ_1	$D^0\pi^0$	(64.7 ± 0.9) %		43
Γ_2	$D^0\gamma$	(35.3 ± 0.9) %		137

$$Q^2 \leq \frac{1}{R^2} \qquad \omega < \omega_{max} \approx \frac{\gamma}{R}, \quad q_\perp \leq \frac{1}{R}$$

$$f_{\gamma/e}(\omega_e) = \frac{\alpha_{em}}{\pi\,\omega_e} \int \frac{\mathrm{d}Q^2}{Q^2} \left[\left(1 - \frac{\omega_e}{E_e} + \frac{\omega_e^2}{2E_e^2} \right) - \left(1 - \frac{\omega_e}{E_e} \right) \frac{Q^2_{min}}{Q^2} \right]$$

$$f_{\gamma/A}(\omega_A) = \frac{Z^2\alpha}{\pi^2} \int \mathrm{d}^2 b\, \frac{1}{b^2 v^2 \omega_A} \left[\int \mathrm{d}u\, u^2 F_A \left(\sqrt{\frac{\left(\frac{b\omega_A}{\gamma_L}\right)^2 + u^2}{b^2}} \right) \frac{1}{\left(\frac{b\omega_A}{\gamma_L}\right)^2 + u^2} J_1(u) \right]^2 ,$$

Interaction Lagrangians

Cao, Du, Guo. J.Phys.G 51 (2024) 10, 105002

- For the charged sector we have the following interaction Lagrangians:

$$\mathscr{L}_{DD\gamma} = (\partial_\mu D^+ + ieA_\mu D^+)(\partial^\mu D^- - ieA^\mu D^-)$$

$$\mathscr{L}_{DD^*\gamma} = -ig_{\gamma D^+ D^{*-}} F_{\mu\nu} \epsilon^{\mu\nu\alpha\beta} (D^{*-}_\alpha \overleftrightarrow{\partial}_\beta D^+ + D^- \overleftrightarrow{\partial}_\beta D^{*+}_\alpha)$$

Where $g_{\gamma D^+ D^{*-}} = -0.035$ GeV^{-1}.

- For the neutral sector we have:

$$\mathscr{L}_{D^0 D^{*0}\gamma} = -ig_{\gamma D^0 D^{*0}} F_{\mu\nu} \epsilon^{\mu\nu\alpha\beta} (\bar{D}^{*0}_\alpha \overleftrightarrow{\partial}_\beta D^0 + \bar{D}^0 \overleftrightarrow{\partial}_\beta D^{*0}_\alpha)$$

Where $g_{\gamma D^0 \bar{D}^{*0}} = 0.142$ GeV^{-1}.

Backup

$$G_{ii} = \frac{1}{16\pi^2}\left\{\alpha_i + \log\left(\frac{m_1^2}{\mu^2}\right) + \frac{m_2^2 - m_1^2 + s}{2s}\log\left(\frac{m_2^2}{m_1^2}\right) + \frac{b}{\sqrt{s}}\left[\log\left(\frac{s - m_2^2 + m_1^2 + 2b\sqrt{s}}{-s + m_2^2 - m_1^2 + 2b\sqrt{s}}\right) + \log\left(\frac{s + m_2^2 - m_1^2 + 2b\sqrt{s}}{-s - m_2^2 + m_1^2 + 2b\sqrt{s}}\right)\right]\right\}.$$

$$\alpha_H(P) = -1.3, \quad \alpha_H(V) = -2.07$$

Form factors

Lebiedowicz, Nachtmann, Szczurek. Phys. Rev. D 98, 014001 (2018).

- We include form factors at the vertices
- Monopole form factors:

$$F(q^2) = \frac{\Lambda^2 - m_{D^{(*)}}^2}{\Lambda^2 - q^2}$$

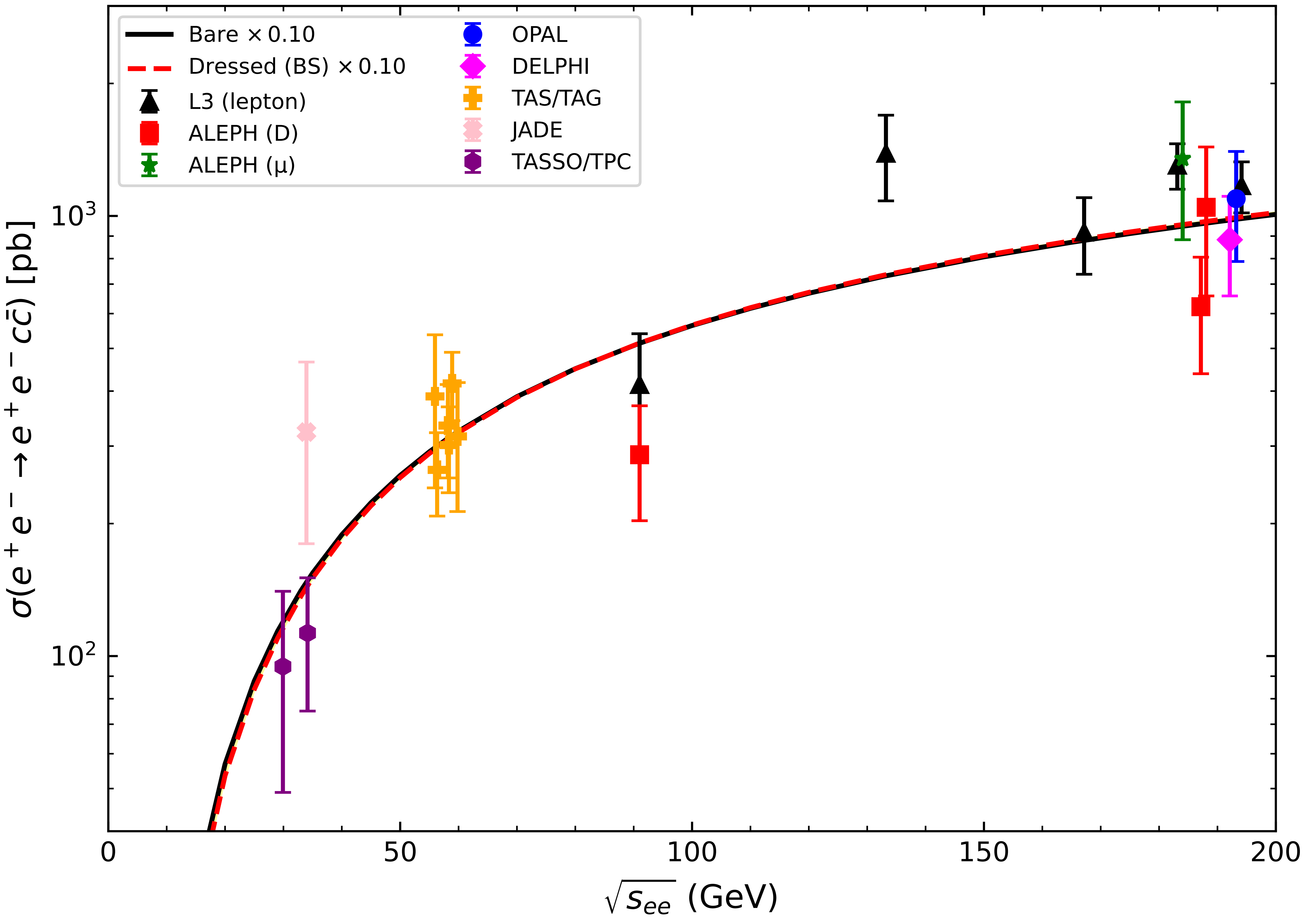
- q is the exchange meson four momentum. Λ is the cutoff parameter. This choice guarantees that $F(m_{D^{(*)}}^2) = 1$ when the exchanged meson is on-shell.
- We use a similar form factor for the neutral channel

$$F(q^2) = \frac{\Lambda^2 - m_{D^{0*}}^2}{\Lambda^2 - q^2}$$

$\Lambda \in [1.0, 1.2]$ GeV value obtained similarly as in *Phys.Rev.D* 110 (2024) 3, 034037

LEP data fitting

We normalize the overall cross sections form factor to LEP data

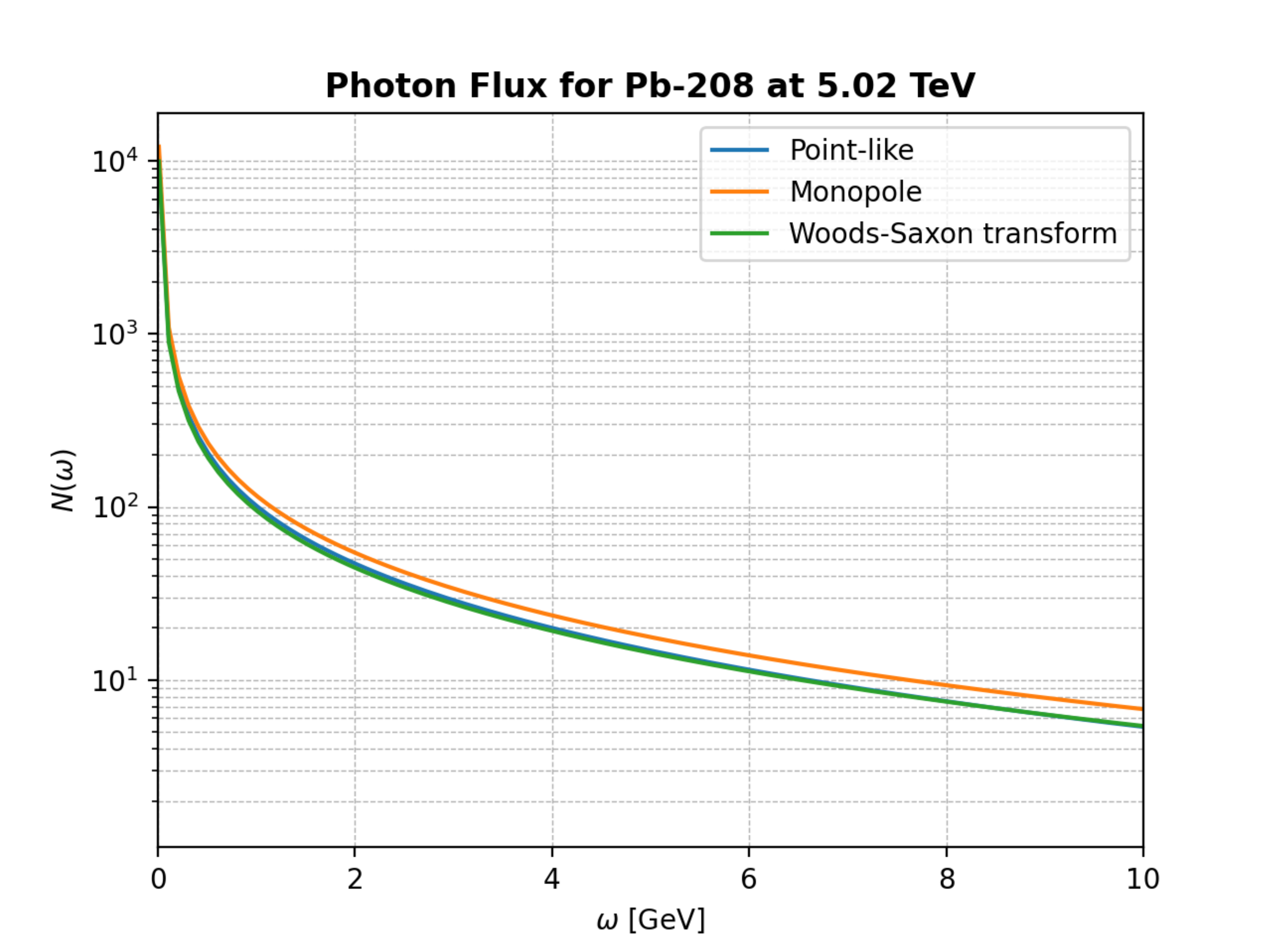


Equivalent photon approximation

$$\sigma(s_1 s_2 \rightarrow s_1 + X + s_2) = \int d\omega_1 d\omega_2 n_1(\omega_1) n_2(\omega_2) \sigma_{\gamma\gamma\rightarrow X}(W)$$

- $W^2 = 4\omega_1\omega_2$
- $n(\omega)$ depends on the source's features
- We can change variables from ω_1, ω_2 to W, Y using $\omega_1 = (W/2)e^{Y}, \omega_2 = (W/2)e^{-Y}$
- This gives the EPA as:

$$\sigma = \int dW dY \frac{W}{2} n_1(\omega_1) n_2(\omega_2) \sigma_{\gamma\gamma\rightarrow X}(W)$$



Minimal coupled channels for $D\bar{D}$ production

- We consider only the two channels $|D^+D^-\rangle$ and $|D^0\bar{D}^0\rangle$
- Isospin structure $|D\bar{D}(I=0)\rangle \sim (|D^+D^-\rangle + |D^0\bar{D}^0\rangle)/\sqrt{2}$
- Not yet $D_s\bar{D}_s, \dots$

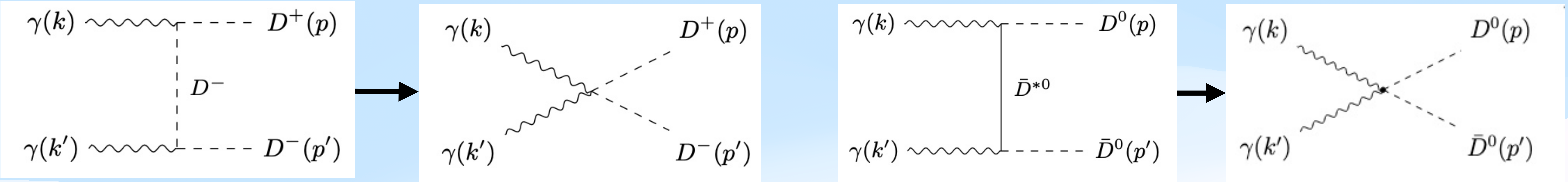
We are interested in computing observables and using effective Lagrangians coupled to photons:

Particle basis!

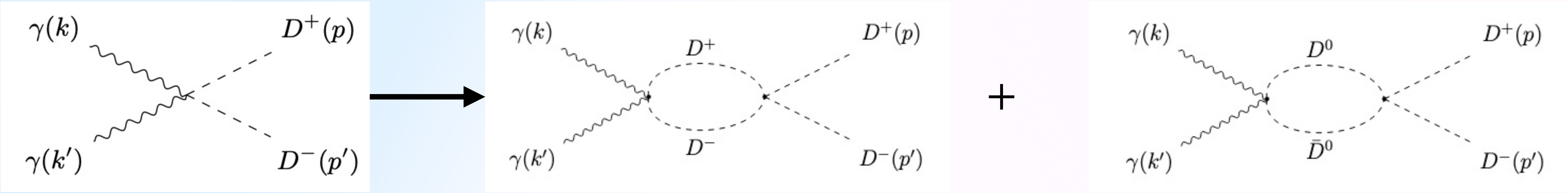
Contact approximation

Wang, et al. Phys.Rev.D 103 (2021) 5, 054008

Near-threshold W, $|\vec{q}\,|^2 \ll m_D^2$ so that our exchange diagrams all approximate a contact term



We can then turn on FSI for contact interactions



Project structure

- Objective: To build a coupled-channel scattering framework for hidden charm $0^{++}, 2^{++}$ sectors

- Processes of interest: $\gamma\gamma \to D^{(*)}\bar{D}^{(*)}, \quad \gamma\gamma \to D_s^{(*)}\bar{D}_s^{(*)}$

- Strategy:

  A. Compute tree-level amplitudes (kernels) for PP, VV and PP ↔ VV

  B. Apply partial wave/ spin projection to obtain $V_J(s)$

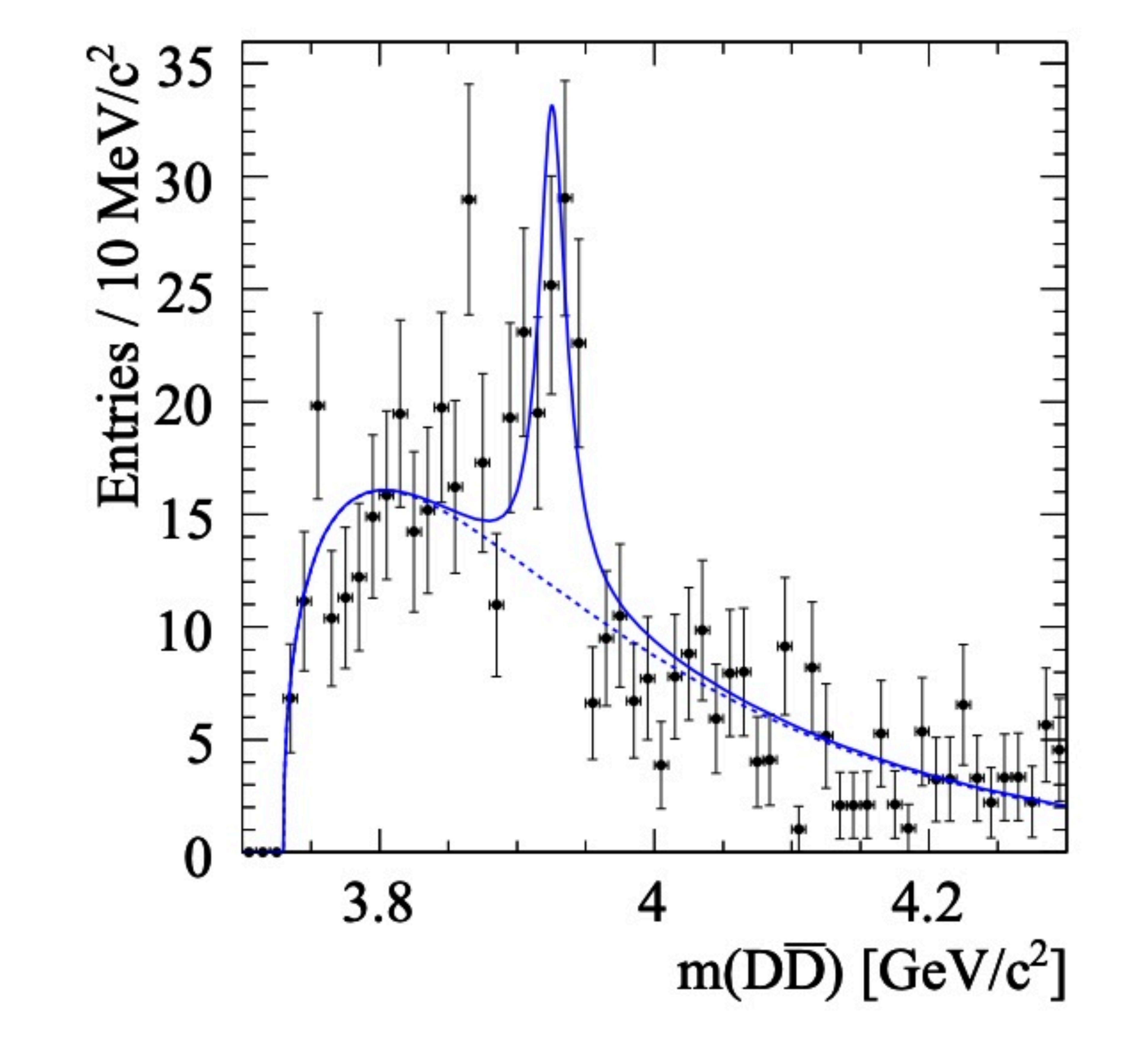
  C. Unitarize to obtain $T_J(s)$, poles, couplings and line shapes

- Current status:
  - Main amplitudes obtained for all blocks
  - Bethe-Salpeter numerical solutions for $PP \to PP, \quad VV \to VV$
  - Mixed $PP \leftrightarrow VV$ still under development

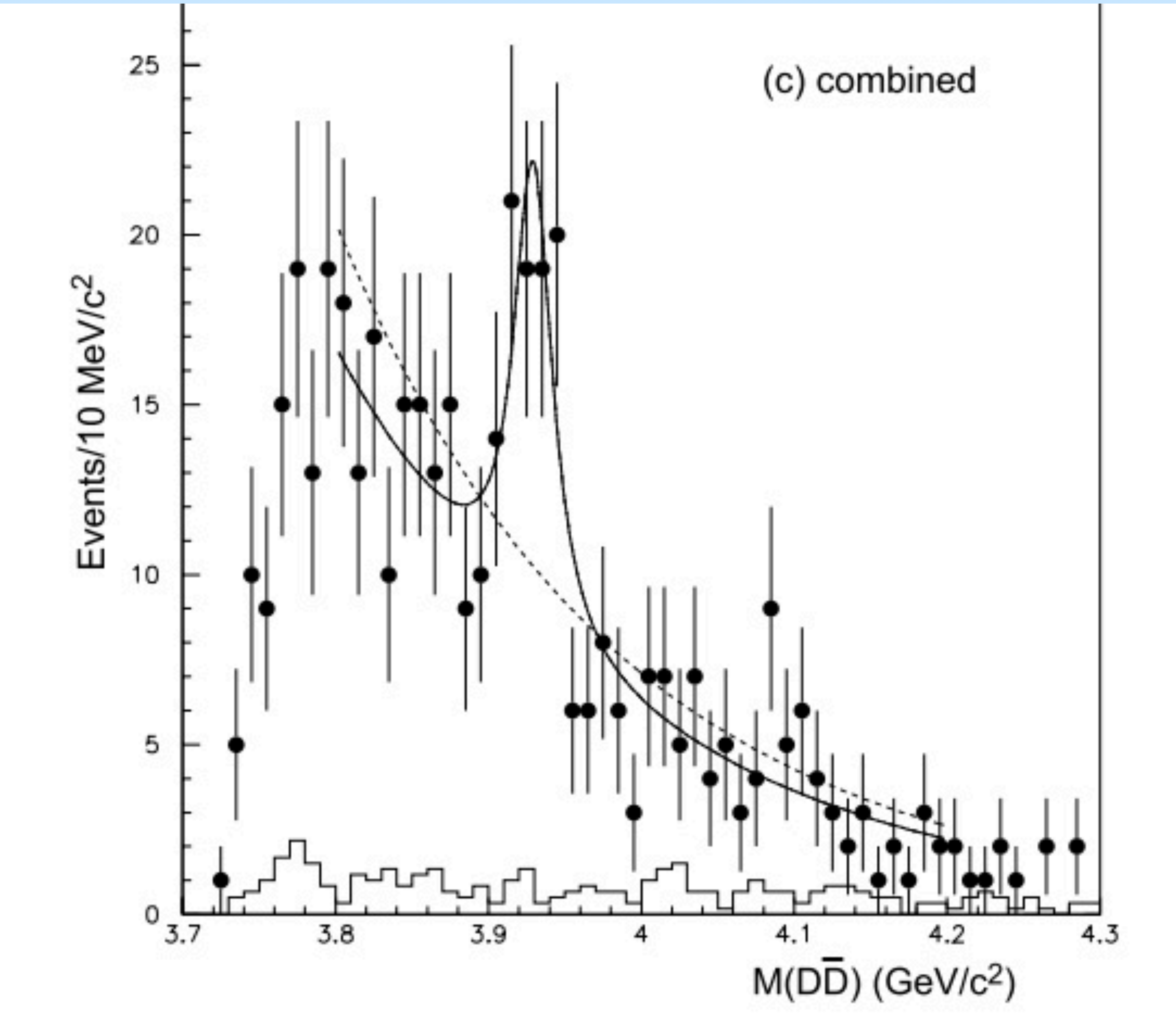
Experiments and data available

BaBar Collaboration. Phys.Rev.D 81 (2010) 092003

Belle Collaboration. Phys.Rev.Lett. 96 (2006) 082003



BaBar



Belle

From amplitudes to T matrix using Bethe-Salpeter

- Fix quantum numbers ($I = 0$, s-wave) and build $V(s)$ from projected amplitudes

$$T(s) = V(s) + V(s)G(s)T(s) \longrightarrow T(s) = [1 - V(s)G(s)]^{-1}V(s)$$

- Solve the coupled channel BSE
- $G(s)$ diagonal matrix of two-meson loop functions. In dimensional regularization it is written in closed form that depends on α_i and scale μ.
- Physics outputs:
  - Poles from $det[1 - VG] = 0$ (bound states/resonances)
  - Residues give channel couplings
  - The same physics that generate threshold effects relevant for $\gamma\gamma$ production

PP sector

Gamermann, et al. Phys.Rev.D 76 (2007) 074016

- We use the PP→ PP amplitudes given in Phys.Rev.D 76 (2007) 074016 for our pseudoscalar sector kernel $V_{ij}(s)$. They are obtained from the Lagrangian:

$$\mathcal{L} = \frac{1}{12f^2}\left(\mathrm{Tr}\left(J_{88\mu}J^{\mu}_{88} + 2\,J_{\bar{3}3\mu}J^{\mu}_{88} + J_{3\bar{3}\mu}J^{\mu}_{3\bar{3}}\right) + \frac{8}{3}\gamma\,J_{\bar{3}1\mu}J^{\mu}_{13} + \frac{4}{\sqrt{3}}\gamma\left(J_{\bar{3}1\mu}J^{\mu}_{83} + J_{\bar{3}8\mu}J^{\mu}_{13}\right) + 2\gamma\,J_{\bar{3}8\mu}J^{\mu}_{83} + \psi_5\,J_{\bar{3}3\mu}J^{\mu}_{\bar{3}3} + \mathcal{L}_{\mathrm{mass}}\right).$$

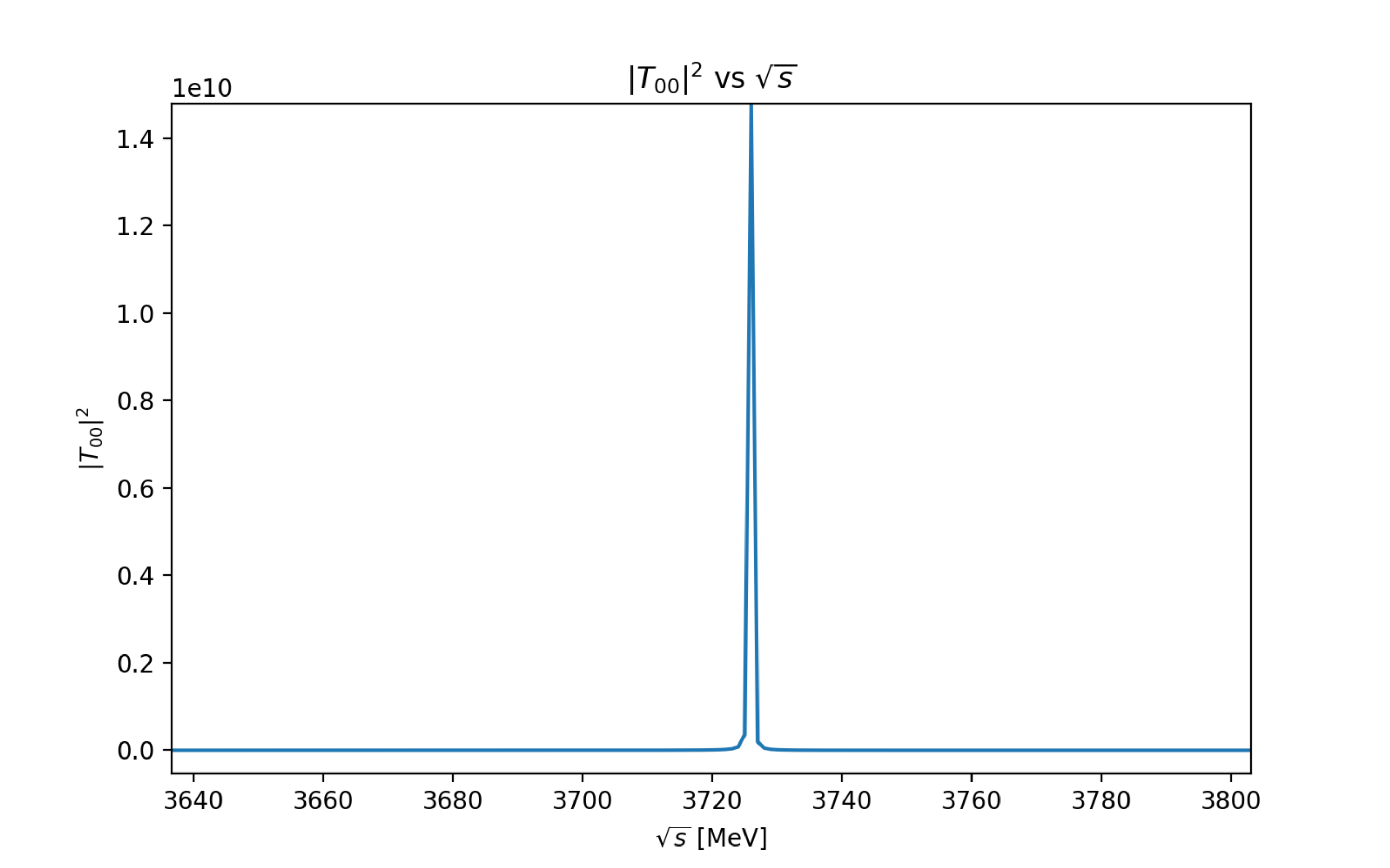
- The possible channels for $I = 0$ are $\pi\pi, K\bar{K}, \eta\eta, \eta\eta_c, D\bar{D}, D_s\bar{D}_s$.
- We can have a $J^P = 0^+$ state.

PP sector: minimal $D\bar{D} - D_s\bar{D}_s$ coupled system

- Work in $I = 0$, s-wave (0^{++} sector as baseline)
- 2 channel basis: $1 \equiv D\bar{D}, \quad 2 \equiv D_s\bar{D}_s$
- After computing PP amplitudes, the kernel is organized as:

$$V(s) = \begin{pmatrix} A_1(s) & A_3(s) \\ A_3(s) & A_2(s) \end{pmatrix}$$

With
$A_1(s) = \langle D\bar{D} | t | D\bar{D} \rangle, \quad A_2(s) = \langle D_s\bar{D}_s | t | D_s\bar{D}_s \rangle, \quad A_3(s) = \langle D\bar{D} | t | D_s\bar{D}_s \rangle$



- With BSE, we get $T(s)$

VV sector

Molina, Oset. Phys.Rev.D 80 (2009) 114013

- We use the VV→ VV amplitudes given in Phys.Rev.D 80 (2009) 114013 for our Vector sector kernel $V_{ij}(s)$. They are obtained from the Lagrangian coming from the Hidden Gauge Symmetry formalism:

$$\mathcal{L} = -\frac{1}{4}\langle V_{\mu\nu}V^{\mu\nu}\rangle$$

- For the $I = 0, \quad J = 0$ there are many possible channels $D^*\bar{D}^*, D_s^*\bar{D}_s^*, K^*\bar{K}^*, \rho\rho, \omega\omega, \phi\phi, J/\psi J/\psi, \omega J/\psi, \psi J/\psi$.

- We can, in principle, have $J^P = 0^+, 2^+$ states, but we start working with 0^+.

VV sector: minimal $D^*\bar{D}^* - D_s^*\bar{D}_s^*$ coupled system

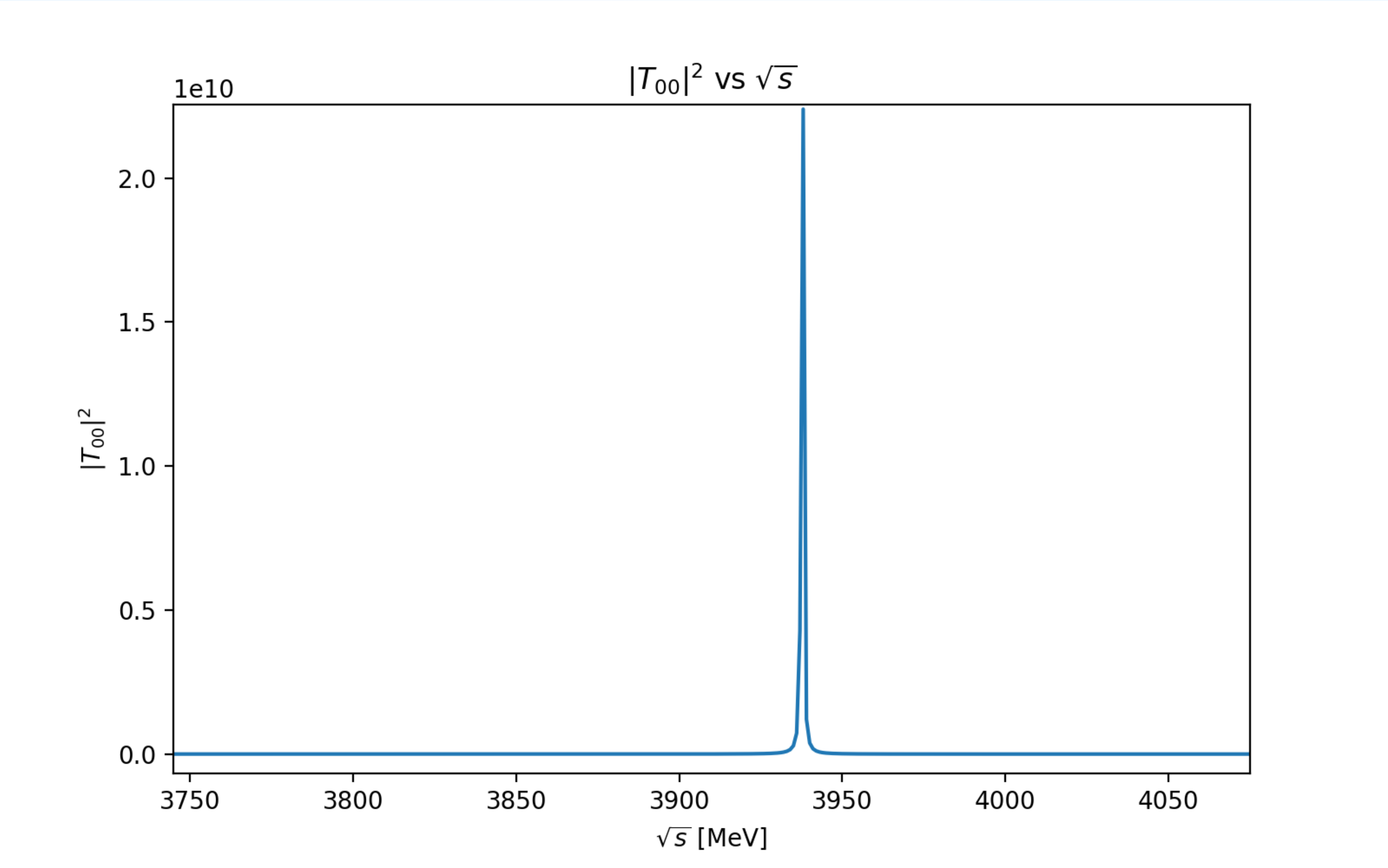
- Work with VV interactions already given in isospin basis and s-wave projected ($I = 0, J = 0$)
- 2 channel basis: $1 \equiv D^*\bar{D}^*$, $2 \equiv D_s^*\bar{D}_s^*$
- Similarly, after computing VV amplitudes, th

$$V(s) = \begin{pmatrix} A_1(s) & A_3(s) \\ A_3(s) & A_2(s) \end{pmatrix}$$

With

$$A_1(s) = \langle D^*\bar{D}^* | t | D^*\bar{D}^* \rangle, \quad A_2(s) = \langle D_s^*\bar{D}_s^* | t | D_s^*\bar{D}_s^* \rangle, \quad A_3(s) = \langle D^*\bar{D}^* | t | D_s^*\bar{D}_s^* \rangle$$

- With BSE, we get $T(s)$ (now with $G(s)$ for two vectors)



Mixed block $D\bar{D} \to D^*\bar{D}^*$

Martinez, et al. Phys.Rev.D. 90, 114023

- We use the Lagrangians given in Phys.Rev.D 90 (2014) 114023 to compute our amplitudes. We then project the amplitudes onto s-wave and spin 0 components for kernels $V_{ij}(s)$. The Lagrangians are:

$$\mathscr{L}_{PPV} = -ig_{PPV}\langle V^\mu [P, \partial_\mu P]\rangle,$$

$$\mathscr{L}_{VVP} = \frac{g_{VVP}}{\sqrt{2}}\epsilon^{\mu\nu\alpha\beta}\langle \partial_\mu V_\nu \partial_\alpha V_\beta P\rangle$$